R-parity Violation and Light Neutralinos at ANUBIS and MAPP

work with Herbert K. Dreiner and Zeren Simon Wang

arXiv: 2008.07539

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Outline

A Massless Neutralino

Neutralino Mass Bound

- Lower neutralino mass bound [Abdallah, et al. 2003 arXiv:hep-ex/0311019]

$$m_{\tilde{\chi}_1^0} > 46\,\mathrm{GeV}$$

based on chargino mass bounds (and subsequently $|\mu|$ and M_2), and unification of gauge couplings at large energy scale

$$M_1 = \frac{5}{3}\tan^2\theta_W M_2 \approx \frac{1}{2}M_2$$

- Dropping the assumption, M_1 is a free parameter and light, bino-like neutralinos are possible and consistent with laboratory bounds [Dreiner, et al. 2009 arXiv:0901.3485]
- Cosmological bounds exclude a stable light neutralino [Dreiner, et al. 2009 arXiv:0901.3485], [Barman, et al. 2017 arXiv:1703.03838]

$$0.7\,\mathrm{eV} < m_{\tilde{\chi}_1^0} < 34\,\mathrm{GeV}$$

RPV Superpotential W

$$W_{RPV} = \kappa_i L_i H_u + \lambda_{ijk} L_i L_j \overline{E}_k + \lambda'_{ijk} L_i Q_j \overline{D}_k + \lambda''_{ijk} \overline{U}_i \overline{D}_j \overline{D}_k$$

Estimated Number of Neutralino Events

Decay Topology

- Prompt $M \to \tilde{\chi}_1^0 + X$, Displaced $\tilde{\chi}_1^0 \to M + l$
- Assume that neutralino is LSP, produced singularly and degenerate sfermion masses

Simulation Procedure

- Produced neutralinos

$$N_{\tilde{\chi}_1^0}^{\text{prod}} = \sum_M N_M \cdot \Gamma(M \to \tilde{\chi}_1^0 + X) \cdot \tau_M$$

- Observable neutralinos

$$N_{\tilde{\chi}_1^0}^{\text{obs}} = N_{\tilde{\chi}_1^0}^{\text{prod}} \cdot \text{Br}(\tilde{\chi}_1^0 \to \text{charged}) \cdot \langle P[\tilde{\chi}_1^0 \text{ in d.r.}] \rangle$$

$\to$ 2 non-zero couplings λ'_{ijk} are required

- Use Pythia 8.243 for a Monte Carlo simulation

$$\langle P[\tilde{\chi}_1^0 \text{ in d.r.}] \rangle = \frac{1}{N_{MC}} \sum_i^{N_{MC}} e^{-\frac{L_{T,i}}{\lambda_i}} \cdot \left(1 - e^{-\frac{L_{I,i}}{\lambda_i}}\right)$$

- Assume zero background and 100% detection efficiency

ANUBIS - AN Underground Belayed In-Shaft search experiment

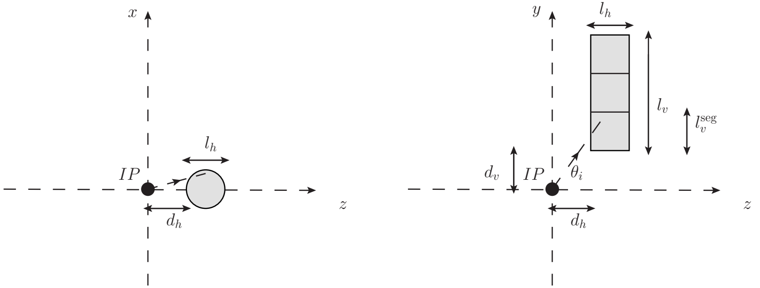


Figure: A sketch of the geometry of ANUBIS from a sideway- and topdown-view [Hirsch, Wang 2020 arXiv:2001.04750]

Geometry

- Cylindrical detector in PX14 installation shaft: $d_v = 24\,\mathrm{m}$ ($d_h = 5\,\mathrm{m}$), $l_v = 56\,\mathrm{m}$ ($l_h = 18\,\mathrm{m}$), $l_v^{\mathrm{seg}} = 18.67\,\mathrm{m}$
- 4 tracking stations divide into 3 segments
- Integrated luminosity $3\,\mathrm{ab}^{-1}$

ANUBIS - Decay Probability

Approximating Fiducial Volume

[Hirsch, Wang 2020 arXiv:2001.04750]

- A segment is missed for

$$\tan\theta_i \le \frac{d_v + (j-1)\cdot l_v^{\text{seg}}}{d_h + l_h}, \qquad \tan\theta_i \ge \frac{d_v + j\cdot l_v^{\text{seg}}}{d_h}$$

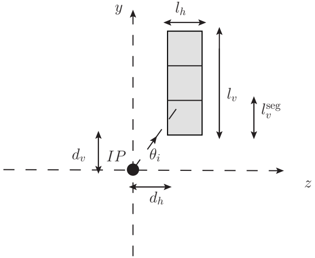
- 3 contributions P_j from each segment

$$P[(\tilde{\chi}_1^0)_i \text{ in d.r.}] = \sum_{j=1}^{3} \frac{\delta\phi^j}{2\pi} \cdot e^{-\frac{L_{T,i}^j}{\lambda_i^z}} \cdot \left(1 - e^{-\frac{L_{I,i}^j}{\lambda_i^z}}\right)$$

- Lengths projected onto beam axis are

$$L_{T,i}^j = \min\left[\max\left(d_h, \frac{d_v + (j-1)\cdot l_v^{\text{seg}}}{\tan\theta_i}\right), d_h + l_h\right]$$

$$L_{I,i}^j = \min\left[\max\left(d_h, \frac{d_v + j\cdot l_v^{\text{seg}}}{\tan\theta_i}\right), d_h + l_h\right] - L_i^j$$



MAPP - MoEDAL Apparatus for the detection Penetrating Particles

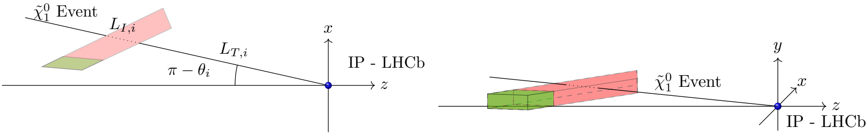


Figure: Sketch of the experimental setup of MAPP1 and MAPP2 [Dreiner, Günther, Wang 2020 arXiv:2008.07539]

Geometry

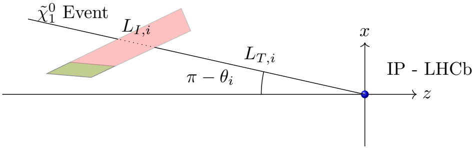
- Located in UGCI gallery at IP8 next to MoEDAL
- Variable position of MAPP1, 5° to 25°
- Integrated luminosities $30\,\mathrm{fb}^{-1}$ and $300\,\mathrm{fb}^{-1}$

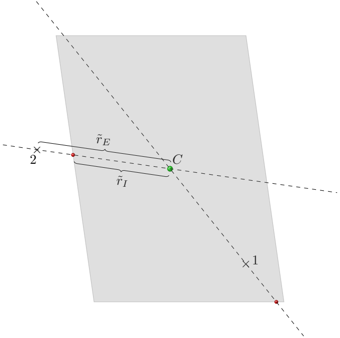
MAPP - Decay Probability

Irregular Orientation of MAPP

- Especially MAPP2 is not well approximated
- ΔL between IP and Detector $\sim 30\,\mathrm{m}$

→ An application computes L_T and L_I





Observation Condition

- Event angles (ϕ, θ) characterize a line hitting the extended plane of detector surface
  → plane hit at $\mathbf{x}_{\mathrm{Hit}}$
- If $\tilde{r}_E = |\mathbf{x}_{\mathrm{Hit}} - \mathbf{x}_C| < \tilde{r}_I$, surface is hit

Benchmark Scenarios

Benchmark 1

- Production via λ'_{122}

$$D_s^{\pm} \to \widetilde{\chi}_1^0 + e^{\pm}$$

- Neutralino Decay via λ'_{112} and λ'_{122}
  Visible final states:

$$\widetilde{\chi}_1^0 \to e^{\pm} + (K^{\mp}, K^{*\mp}) \qquad \text{via } \lambda'_{112}$$

Invisible final states:

$$\widetilde{\chi}_1^0 \to \begin{cases} \nu_e + (\eta, \eta', \phi) & \text{via } \lambda'_{122} \\ \nu_e + (K_L^0, K_S^0, K^{*0}) & \text{via } \lambda'_{112} \end{cases}$$

Benchmark 2

- Production via λ'_{131}

$$B^0 \to \widetilde{\chi}_1^0 + \nu_e$$

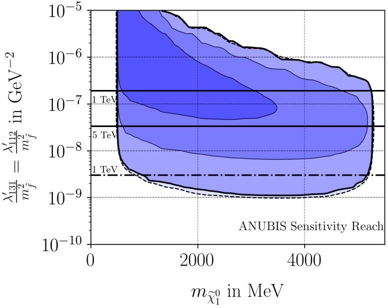
- Neutralino Decay via λ'_{112}
  Visible final states:

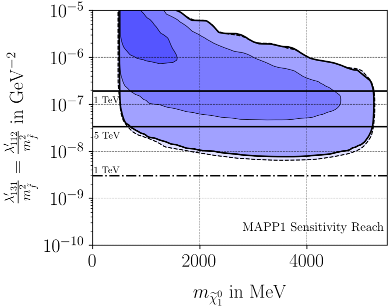
$$\widetilde{\chi}_1^0 \to e^{\pm} + (K^{\mp}, K^{*\mp})$$

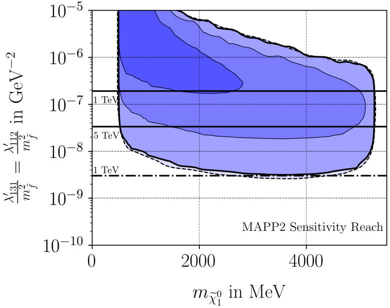
Invisible final states:

$$\widetilde{\chi}_1^0 \to \nu_e + (K_L^0, K_S^0, K^{*0})$$

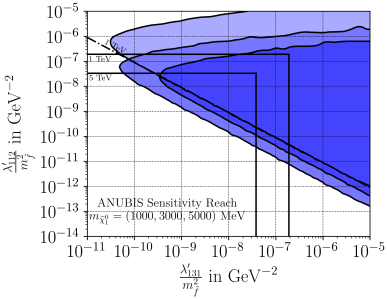
$\lambda'/m_{\tilde{f}}^2$ vs. $m_{\tilde{\chi}_1^0}$

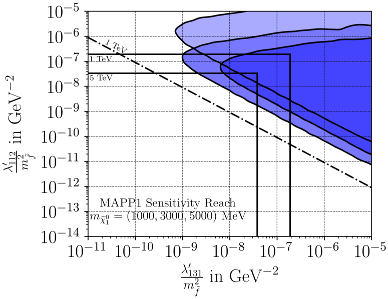


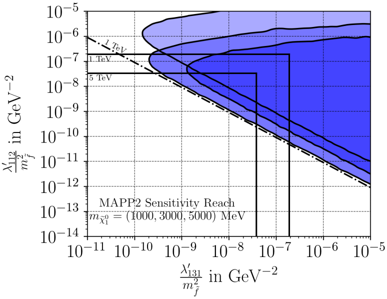




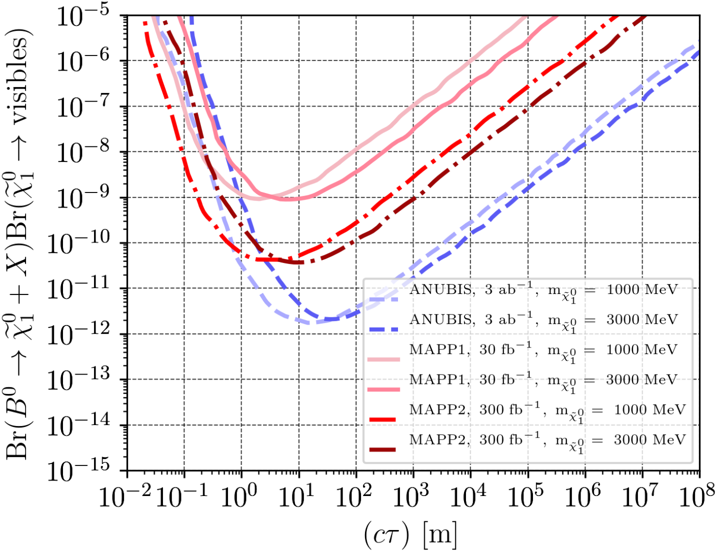
$\lambda'_D/m^2_{\tilde{f}}$ vs. $\lambda'_P/m^2_{\tilde{f}}$





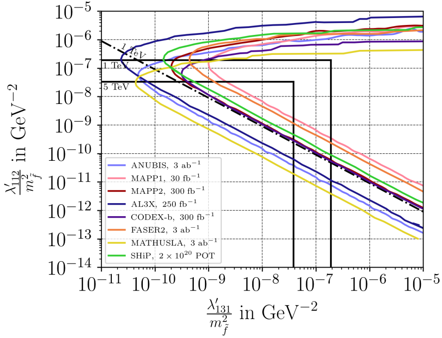


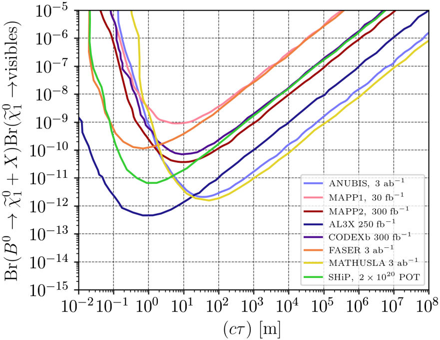
Br vs. $c\tau$



$\mathrm{Br}(B^0 \to \tilde{\chi}_1^0 + X)\mathrm{Br}(\tilde{\chi}_1^0 \to \text{visibles})$
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7} 10^{8}
$(c\tau)$ [m]
ANUBIS, 3 ab^{-1}, $m_{\tilde{\chi}_1^0}$ = 1000 MeV
ANUBIS, 3 ab^{-1}, $m_{\tilde{\chi}_1^0}$ = 3000 MeV
MAPP1, 30 fb^{-1}, $m_{\tilde{\chi}_1^0}$ = 1000 MeV
MAPP1, 30 fb^{-1}, $m_{\tilde{\chi}_1^0}$ = 3000 MeV
MAPP2, 300 fb^{-1}, $m_{\tilde{\chi}_1^0}$ = 1000 MeV
MAPP2, 300 fb^{-1}, $m_{\tilde{\chi}_1^0}$ = 3000 MeV

Comparison, $m_{\tilde{\chi}_1^0} = 3000\,\mathrm{MeV}$



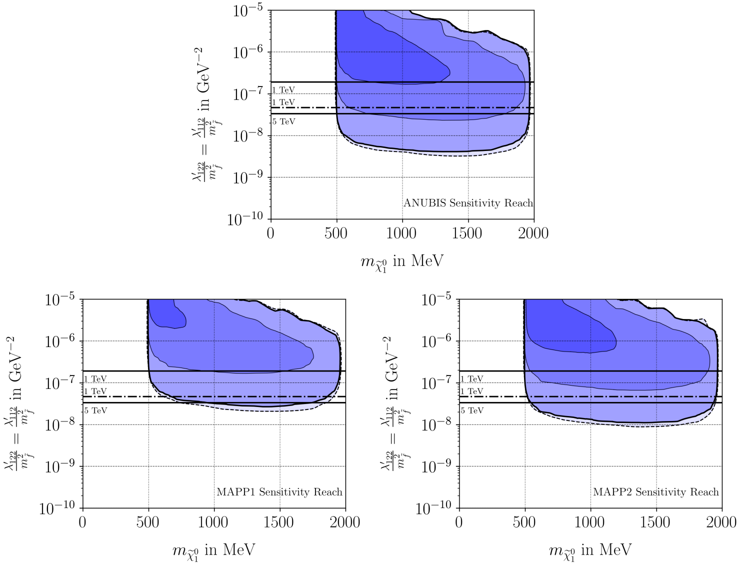


Conclusion

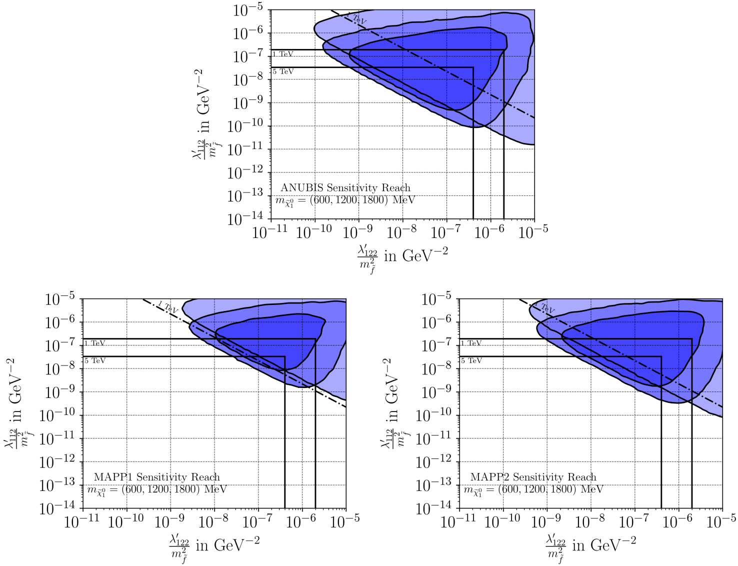
- Large luminosity at HL-LHC allows for LLP discovery.
- Both `ANUBIS` and `MAPP` are sensitive to light neutralinos in R-parity violating supersymmetry beyond current bounds ($M \to \tilde{\chi}_1^0 + X$, $\tilde{\chi}_1^0 \to M + l$)
- `MAPP2` extends sensitivity of `MAPP1` significantly, `ANUBIS` is most promising
- Compared `ANUBIS` and `MAPP` to other proposed experiments the sensitivity reach is complementary, but differs in optimal decay lengths
- Br vs. $c\tau$ estimates are extendable to related decay topologies

Thank you!

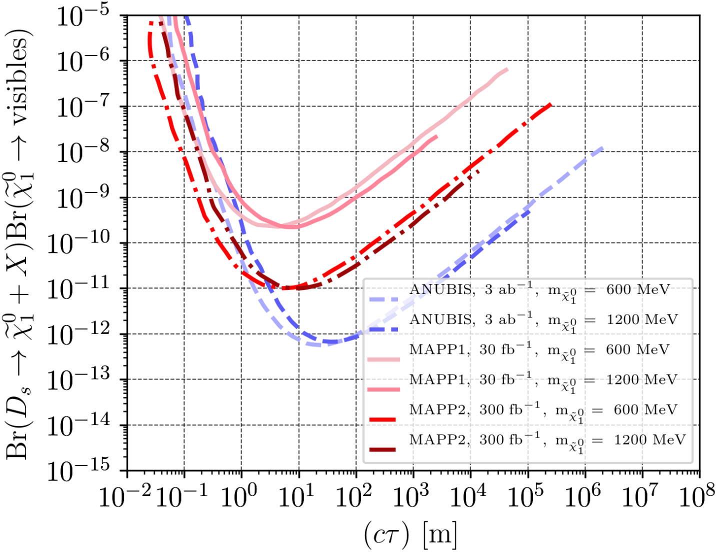
Charmed Benchmark - $\lambda'/m_{\tilde{f}}^2$ vs. $m_{\tilde{\chi}_1^0}$



Charmed Benchmark - $\lambda'_D/m^2_{\tilde{f}}$ vs. $\lambda'_P/m^2_{\tilde{f}}$



Charmed Benchmark - Br vs. $c\tau$



Comparison, $m_{\tilde{\chi}_1^0} = 1200\,\mathrm{MeV}$